Specification

Title of the Invention

Astigmatic-power Spectacle Lens

Background of the Invention

The present invention relates to a single-vision spectacle
lens to correct eyesight and particularly, to an astigmatic-power
lens having a cylindrical power to correct astigmatism of an
eye.

An astigmatic-power lens has a cylindrical power to correct
astigmatism of an eye. In a conventional astigmatic-power lens,
a front surface (an object side) is a spherical surface or a
rotationally-symmetrical aspherical surface and a back surface
(an eye side) is processed to be a toric surface to have a
difference between the refractive powers in two orthogonal
directions in a plane perpendicular to an optical axis, thereby
correcting astigmatism.

However, in the above-described conventional
astigmatic-power lens, since the rotationally-asymmetrical
component to add the cylindrical power is given by the toric
surface, a good transmitting optical performance is given in
the directions of a first principal meridian along which the

minimum surface refractive power is obtained and a second principal meridian along which the maximum surface refractive power is obtained, while a sufficient transmitting optical performance cannot be given in other directions between the first

5   and second principal meridians.

Summary of the Invention

It is therefore an object of the present invention to

10   provide an astigmatic-power spectacle lens, which is capable of having a sufficient optical performance in any direction even if the lens has a cylindrical power to correct astigmatism of an eye.

For the above object, according to the present invention,

15   there is provided an improved single-vision astigmatic-power spectacle lens to correct eyesight, which includes:

a front surface; and

a back surface,

wherein at least one of the front and back surfaces is

20   a rotationally-asymmetrical aspherical surface that has a rotationally-asymmetrical component to correct the aberrations in the directions between first and second principal meridians of the rotationally-asymmetrical surface caused by adding the cylindrical power.

25   With this construction, since at least one of front and

back surfaces is a rotationally-asymmetrical surface, the aberration caused by adding the cylindrical power can be corrected.

Further, the rotationally-asymmetrical surface may further include an another rotationally-asymmetrical component to add the cylindrical power for correcting astigmatism of an eye.

When the one surface has two rotationally-asymmetrical components, the other surface may be a rotationally-symmetrical surface, preferably, a spherical surface.

Further, in order to respond to various combinations of spherical power, cylindrical power and cylindrical axis direction, it is desirable that semifinished lens blanks whose front surfaces are finished are stockpiled and a back surface of the selected semifinished lens blank is processed according to the customer's specification in order to shorten delivery times.

The present invention may be also defined as follows. Namely, when a sag z(h, θ) of the rotationally-asymmetrical surface at a point (h, θ) with respect to an x-y plane is expressed as a function of the angle θ while fixing the distance h, the curve of the function has a larger gradient in close to the local maximum and a smaller gradient in close to the local minimum as compared with the curve interpolated by the sine curve in any distances h within the range of 10 ≤ h ≤ 20.

The z-axis is a normal to the rotationally-asymmetrical surface at a framing reference point that is the origin of the x-y-z coordinate system and is coincident with a pupil position of a user when the spectacle lens is installed on a frame.

5   The x-axis is coincident with a first principal meridian of the rotationally-asymmetrical surface along which the minimum surface refractive power is obtained.

The y-axis is coincident with a second principal meridian of the rotationally-asymmetrical surface along which the maximum surface refractive power is obtained.

Symbol h is a distance from the origin in the x-y plane, and θ is an angle of the line passing the origin and the point (h, θ) with respect to the x-axis in the x-y plan.

Further, according to another definition, the present invention is characterized in that the following condition (1) is satisfied in any distances h within the range of $10 \leq h \leq 20$:

$$z(h,45) < \{f(h)+g(h)\}/2 \quad \cdots (1)$$

where

20     $f(h)$ is the sag $z(h, 0)$ on the x-axis, and

$g(h)$ is the sag $z(h, 90)$ on the y-axis.

When the spectacle lens is a negative lens, it is desirable that the following condition (2) is satisfied in any distances h within the range of $10 \leq h \leq 20$:

25     $-0.00010 < [z(h,45)-\{f(h)+g(h)\}/2]$

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$$/[\{f(h)-g(h)\}\times h\times CYL]<-0.00008\ \cdots(2)$$

where

CYL (unit: Diopter) is a cylindrical power.

Description of the Accompanying Drawings

Fig. 1 is a side sectional view of a spectacle lens embodying the invention;

Fig. 2 is a front view of the spectacle lens of Fig. 1;

Fig. 3 is a graph showing a sag of a back surface of the lens of Fig. 1 expressed by a function of the angle;

Fig. 4 is a graph showing calculated results about a condition (1) for the spectacle lens of a first embodiment;

Fig. 5 is a graph showing calculated results about a condition (2) for the spectacle lens of the first embodiment;

Fig. 6 is a three-dimension graph showing an average refractive power error of the spectacle lens of the first embodiment;

Fig. 7 is a three-dimensional graph showing astigmatism of the spectacle lens of the first embodiment;

Fig. 8 is a two-dimensional distribution map showing astigmatism of the spectacle lens of the first embodiment;

Fig. 9 is a three-dimension graph showing an average refractive power error of the spectacle lens of a first comparative example;

Fig. 10 is a three-dimensional graph showing astigmatism of the spectacle lens of the first comparative example;

Fig. 11 is a two-dimensional distribution map showing astigmatism of the spectacle lens of the first comparative example;

Fig. 12 is a graph showing calculated results about a condition (1) for the spectacle lens of a second embodiment;

Fig. 13 is a graph showing calculated results about a condition (2) for the spectacle lens of the second embodiment;

Fig. 14 is a three-dimension graph showing an average refractive power error of the spectacle lens of the second embodiment;

Fig. 15 is a three-dimensional graph showing astigmatism of the spectacle lens of the second embodiment;

Fig. 16 is a two-dimensional distribution map showing astigmatism of the spectacle lens of the second embodiment;

Fig. 17 is a three-dimension graph showing an average refractive power error of the spectacle lens of a second comparative example;

Fig. 18 is a three-dimensional graph showing astigmatism of the spectacle lens of the second comparative example; and

Fig. 19 is a two-dimensional distribution map showing astigmatism of the spectacle lens of the second comparative example.

Description of the Embodiments

A single-vision spectacle lens embodying the present invention will be described hereinafter. First, a general construction is described with reference to Figs. 1 and 2, and then concrete examples will be shown. Figs. 1 and 2 show a spectacle lens 1 embodying the invention; Fig. 1 is a sectional view and Fig. 2 is a plan view looking from a front surface.

The spectacle lens 1 has a cylindrical power to correct astigmatism of an eye. The front surface 2 of the lens 1 is a spherical surface and the back surface 3 is a rotationally-asymmetrical aspherical surface. On the spectacle lens 1, a framing reference point 4 is defined to be coincident with a pupil position of an eye 5 of a user when the spectacle lens 1 is installed on a frame.

In the drawings, an x-y-z coordinate system whose origin is coincident with the framing reference point 4 is set for defining the back surface 3. The z-axis is a normal to the back surface 3 at the framing reference point 4. The x- and y-axes intersect at a right angle in a plane perpendicular to the z-axis. The x-axis is coincident with a first principal meridian along which the minimum surface refractive power is obtained. The y-axis is coincident with a second principal meridian along which the maximum surface refractive power is obtained.

The back surface 3 has a first rotationally-asymmetrical

component to add the cylindrical power for correcting astigmatism
of an eye and a second rotationally-asymmetrical component to
correct the aberration caused by adding the cylindrical power.
The second component corrects aberration in the direction between
the directions of the first principal meridian (x-axis) and the
second principal meridian (y-axis). Since the back surface 3
has the two rotationally-asymmetrical components, the front
surface 2 is not required to have a complex shape, which allows
the front surface 2 to be spherical. This eases the making of
a semifinished lens blank whose front surface is previously
finished.

As shown in Fig. 2, a two dimensional coordinate of a point
on the back surface 3 is defined by a polar coordinate (h, θ)
where h (unit: mm) is the distance from the z-axis to the point
in the x-y plane and θ (unit: degree) is the angle of the line
passing the origin and the point with respect to the x-axis in
the x-y plane. The sag of the back surface 3 at the point (h,
θ) with respect to the x-y plane is expressed by z(h, θ). The
sag z(h, 0) on the x-axis is f(h) and the sag z(h, 90) on the
y-axis is g(h).

When the sag z(h, θ) is expressed as a function of the
angle θ while fixing the distance h, the variation of the sag
of the lens surface having the first rotationally-asymmetrical
component to add a cylindrical power is like a sine curve as
shown in Fig. 3. In Fig. 3, the sag z(20, θ) of the lens whose

spherical power (SPH) is 6.00 Diopter, cylindrical power (CYL) is 3.00 Diopter and cylindrical axis direction (AX) is 0°. A solid line in the graph represents the data of the spectacle lens 1 of the embodiment and the dotted line indicates a comparative data where the points between the local maximum and the local minimum are interpolated by a sine curve. The curve of the spectacle lens 1 of the embodiment has a larger gradient in close to the local maximum and a smaller gradient in close to the local minimum as compared with the curve interpolated by the sine curve. While the graph of Fig. 3 shows the case of h = 20 only, similar results are obtained in any distance h within the range of 10 ≤ h ≤ 20. The difference between the gradients at the local maximum side and the local minimum side can sufficiently correct the aberrations in the directions between the first and second principal meridians caused by adding the cylindrical power. The difference is the second rotationally-asymmetrical component to correct the aberration caused by adding the cylindrical power. Further, the difference between the sine curve and the function of the embodiment is exaggerated for purpose of illustration in Fig. 3.

The above relationship is numerically expressed as follows. That is, the spectacle lens 1 of the embodiment satisfies the following condition (1) at any distances h within the range of 10 ≤ h ≤ 20.

$$z(h,45) < \{f(h)+g(h)\}/2 \quad \ldots (1)$$

When the sag varies along the sine curve, the sag at 45°, which is an intermediate angle between 0° where the local minimum value f(h) is taken and 90° where the local maximum value g(h) is taken, is equal to the average of the local maximum value

5   and the local minimum value. This is the right side of the condition (1). The condition (1) represents that the sag z(h, 45) of the spectacle lens 11 of the embodiment is smaller than the average value described above. When the condition (1) is satisfied, the sag variation of the back surface 3 has a larger

10   gradient in close to the local maximum and a smaller gradient in close to the local minimum as compared with the curve interpolated by the sine curve.

For the spectacle lens having a negative spherical power, the following condition (2) is satisfied at any distance h within

15   the range of 10 ≤ h ≤ 20;

-0.00010<[z(h,45)-{f(h)+g(h)}/2]

/[{f(h)-g(h)}×h×CYL]<-0.00008 ...(2)

The larger the cylindrical power CYL is, the larger the difference between the local maximum value and the local minimum

20   value is. The condition (2) defines that the magnification of the variation in difference between the sag at 45° and the average value is larger than the magnification of the variation in difference between the local maximum value and the local minimum value. When the condition (2) is satisfied, the aberration can

25   be sufficiently corrected even for the spectacle lens whose

cylindrical power is relatively large.

Next, two embodiments of the spectacle lens 1 embodying the present invention will be described. In the following description, two embodiments and two comparative examples will be described as compared with each other. The sag variation according to the angle θ in each embodiment is not coincident with a sine curve, while that in each comparative example is coincident with a sine curve.

First Embodiment

The spectacle lens of the first embodiment is an astigmatic-power lens having a cylindrical power. Data of the first embodiment is shown in TABLE 1. In the table, SPH denotes a spherical power at a vertex, CYL denotes a cylindrical power, DIA denotes a diameter, CT denotes a center thickness of a lens, N denotes refractive index and R_1 denotes radius of curvature of the front surface. Since the back surface is rotationally-asymmetrical, radii of curvature and sags are different between the x- and y-axis directions. R_{2s} and R_{2c} denote radii of curvature of the back surface in the x- and y-axes directions, respectively. Further, the sag f(h) in the x-axis direction and the sag g(h) in the y-axis direction are expressed as follows:

$$f(h) = \frac{h^2}{R_{2s}\left(1 + \sqrt{\left(1 - (1 + K_s)(1 / R_{2s})^2 h^2\right)}\right)} + A_{4s}h^4$$
$$+ A_{6s}h^6 + A_{8s}h^8 + A_{10s}h^{10} + A_{12s}h^{12}$$

$$g(h) = \frac{h^2}{R_{2c}\left(1 + \sqrt{\left(1 - (1 + K_{sc})(1 / R_{2c})^2 h^2\right)}\right)} + A_{4c}h^4$$
$$+ A_{6c}h^6 + A_{8c}h^8 + A_{10c}h^{10} + A_{12c}h^{12}$$

where K_S and K_C are conic constants in the x- and y-axes directions, respectively, A_{4S}, A_{6S}, A_{8S}, A_{10S} and A_{12S} are aspherical surface

5 coefficients in the x-axis direction and A_{4C}, A_{6C}, A_{8C}, A_{10C} and A_{12C} are aspherical surface coefficients in the y-axis direction.

TABLE 1

SPH	-4.00[Diopter]	CYL	-4.00[Diopter]
DIA	70.0[mm]	CT	1.100[mm]
N	1.665		
R_1	742.500[mm]		
R_{2S}	135.821[mm]	R_{2C}	74.751[mm]
K_S	0.000	K_C	0.000
A_{4S}	-5.18578×10^{-07}	A_{4C}	-5.81866×10^{-07}
A_{6S}	2.30778×10^{-10}	A_{6C}	2.53653×10^{-10}
A_{8S}	-8.38783×10^{-14}	A_{8C}	-1.66820×10^{-13}
A_{10S}	1.59041×10^{-17}	A_{10C}	1.04162×10^{-16}
A_{12S}	0.00000	A_{12C}	0.00000

10   TABLE 1 defines the shape of the back surface 3 in the

x- and y-axes directions only. TABLE 2 shows the sags of the

back surface 3 at the typical points located between the first

principal meridian (x-axis) and the second principle meridian

(y-axis). In TABLE 2, the points are defined by the two

15 dimensional coordinate, not the polar coordinate. Numerals 0

to 35 in the horizontal axis represent distances from the origin

in the x-axis direction, and numerals 0 to 35 in the vertical

axis represent distances from the origin in the y-axis direction.

The sag of back surface of the spectacle lens according

to the first embodiment is determined as follows. Namely, when

the sag $z(h, \theta)$ is expressed as a function of the angle θ while

fixing the distance h, the curve of the sag in the first embodiment

has a larger gradient in close to the local maximum and a smaller

gradient in close to the local minimum as compared with the curve

interpolated by the sine curve for any distance h within the

range of $10 \leq h \leq 20$. Further, TABLE 2 shows the sags within

the range of $0 \leq \theta \leq 90$, while the sags within the range of 90

$\leq \theta \leq 180$ are axially symmetric to the values in TABLE 2 about

the y-axis and the sags within the range of $180 \leq \theta \leq 360$ are

axially symmetric to the values within the range of $0 \leq \theta \leq 180$

about the x-axis.

TABLE 2

SAG	0	5	10	15	20	25	30	35
0	0.000000	0.091744	0.363672	0.807024	1.410464	2.163271	3.057435	4.088614
5	0.167049	0.257987	0.527925	0.968350	1.568335	2.317581	3.208605	–
10	0.666323	0.755276	1.020979	1.455631	2.049437	2.793451	3.682211	–
15	1.493507	1.579555	1.839526	2.266812	2.853457	3.593174	4.485278	–
20	2.645104	2.727772	2.981801	3.402310	3.984375	4.727036	–	–
25	4.123463	4.202986	4.453177	4.872063	5.460559	–	–	–
30	5.949514	6.027860	6.282184	6.716460	–	–	–	–
35	8.204454	–	–	–	–	–	–	–

Fig. 4 is a graph showing calculated results about the

condition (1), which is equal to $z(h,45)-\{f(h)+g(h)\}/2$, for the

spectacle lens of the first embodiment within the range of 0 ≤ h ≤ 35 mm. The graph shows that the values are minus within the range of 10 ≤ h ≤ 20 mm and thus the first embodiment satisfies the condition (1).

Further, Fig. 5 is a graph showing calculated results about the condition (2) within the range of 0 ≤ h ≤ 35 mm. The graph shows that the values of intermediate terms of the condition (2) fall within the range between -0.00010 and -0.00008 and thus the first embodiment satisfies the condition (2).

Figs. 6 and 7 are three-dimensional graphs showing transmitting optical performances of the first embodiment; Fig. 6 shows an average refractive power error and Fig. 7 shows astigmatism of the spectacle lens. In the graphs, plane coordinates represent the distances (unit: mm) of a position on the lens surface from the origin in the x-axis and y-axis, respectively, the vertical axis represents amount of aberration (unit: Diopter). Fig. 8 is a two-dimensional distribution map showing the astigmatism shown in Fig. 7.

First Comparative Example

The spectacle lens of the first comparative example is an astigmatic-power lens that has the same specification (SPH and CYL) as the first embodiment and the distribution of the sag of the back surface of the first comparative example is shown in TABLE 3.

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TABLE 3

SAG	0	5	10	15	20	25	30	35
0	0.000000	0.091744	0.363669	0.807007	1.410409	2.163138	3.057159	4.088100
5	0.167050	0.258347	0.529061	0.970756	1.572511	2.324034	3.217880	–
10	0.666326	0.756419	1.023865	1.461152	2.058582	2.807272	3.701896	–
15	1.493525	1.581995	1.845074	2.276612	2.868903	3.615849	4.517090	–
20	2.645158	2.732056	2.991048	3.417831	4.007900	4.760694	–	–
25	4.123596	4.209704	4.467257	4.894968	5.494374	–	–	–
30	5.949790	6.037685	6.302413	6.748791	–	–	–	–
35	8.204968	–	–	–	–	–	–	–

When the sag $z(h, \theta)$ is expressed as a function of the angle θ while fixing the distance h, the sags at the points between the local maximum and the local minimum are interpolated by the sine curve. That is a difference between the first embodiment and the first comparative example.

Accordingly, the first comparative example does not satisfy the condition (1) because the value of $z(h,45)-\{f(h)+g(h)\}/2$ equals 0, and the condition (2) is not satisfied because the value of the intermediate term of the condition (2) equals 0.

Figs. 9 and 10 are three-dimensional graphs showing transmitting optical performances of the first comparative example; Fig. 9 shows an average refractive power error and Fig. 10 shows astigmatism of the spectacle lens. Fig. 11 is a two-dimensional distribution map showing the astigmatism shown in Fig. 10.

Compared with Figs. 6 to 8, in the first comparative example,

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the contour lines of the astigmatism bend inside in the directions

between the first and second principal meridians, which results

in unnatural defocusing on the periphery of the view field. In

the first embodiment, the contour lines of the astigmatism are

5   almost oval, which results in natural defocusing.

Second Embodiment

A spectacle lens of the second embodiment is an

astigmatic-power lens having a cylindrical power and the

10   specification thereof is shown in TABLE 4.

TABLE 4

SPH	-2.00[Diopter]	CYL	-2.00[Diopter]
DIA	75.0[mm]	CT	1.100[mm]
N	1.665		
R_1	370.000[mm]		
R_{2S}	175.026[mm]	R_{2C}	114.666[mm]
K_S	0.000	K_C	0.000
A_{4S}	-2.68725×10^{-07}	A_{4C}	-4.15750×10^{-07}
A_{6S}	1.31953×10^{-10}	A_{6C}	2.05382×10^{-10}
A_{8S}	-4.59128×10^{-14}	A_{8C}	-7.49654×10^{-14}
A_{10S}	7.53092×10^{-18}	A_{10C}	1.60702×10^{-17}
A_{12S}	0.00000	A_{12C}	0.00000

TABLE 4 defines the shape of the back surface in the x-

15   and y-axes directions only. TABLE 5 shows the sags of the back

surface at the typical points located between the first principal

meridian (x-axis) and the second principle meridian (y-axis).

The sag of back surface of the spectacle lens according

to the second embodiment is determined as follows. Namely, when

the sag z(h, θ) is expressed as a function of the angle θ while

fixing the distance h, the curve of the sag in the first embodiment

has a larger gradient in close to the local maximum and a smaller

gradient in close to the local minimum as compared with the curve

5   interpolated by the sine curve for any distance h within the

range of 10 ≤ h ≤ 20. Further, the sags within the range of

90 ≤ θ ≤ 360 can be obtained in the same manner as described

in the first embodiment.

10   TABLE 5

SAG	0	5	10	15	20	25	30	35
0	0.000000	0.071267	0.283346	0.631734	1.110801	1.715626	2.443103	3.291949
5	0.108807	0.179631	0.390547	0.737250	1.214396	1.817323	2.543088	−
10	0.432921	0.502594	0.710655	1.053355	1.526109	2.124957	2.847426	−
15	0.966451	1.034497	1.238664	1.576016	2.043028	2.636714	3.355327	−
20	1.702529	1.768795	1.968903	2.300817	2.762168	3.351076	−	−
25	2.636301	2.700920	2.897606	3.225169	3.682370	−	−	−
30	3.767231	3.830551	4.025093	4.350463	−	−	−	−
35	5.101280	−	−	−	−	−	−	−

Fig. 12 is a graph showing calculated results about the

condition (1), which is equal to z(h,45)-{f(h)+g(h)}/2, for the

spectacle lens of the second embodiment within the range of 0

15   ≤ h ≤ 35 mm. The graph shows that the values are minus within

the range of 10 ≤ h ≤ 20 mm and thus the second embodiment satisfies

the condition (1).

Further, Fig. 13 is a graph showing calculated results

about the condition (2) within the range of 0 ≤ h ≤ 35 mm. The

20   graph shows that the values of intermediate terms of the condition

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(2) fall within the range between -0.00010 and -0.00008 and thus the second embodiment satisfies the condition (2).

Figs. 14 and 15 are three-dimensional graphs showing transmitting optical performances of the second embodiment; Fig. 14 shows an average refractive power error and Fig. 15 shows astigmatism of the spectacle lens. Fig. 16 is a two-dimensional distribution map showing the astigmatism shown in Fig. 15.

Second Comparative Example

The spectacle lens of the second comparative example is an astigmatic-power lens that has the same specification (SPH and CYL) as the second embodiment and the distribution of the sag of the back surface of the first comparative example is shown in TABLE 6.

TABLE 6

SAG	0	5	10	15	20	25	30	35
0	0.000000	0.071267	0.283346	0.631732	1.110793	1.715607	2.443063	3.291876
5	0.108807	0.179728	0.390852	0.737894	1.215504	1.819020	2.545500	–
10	0.432922	0.502901	0.711427	1.054821	1.528517	2.128560	2.852484	–
15	0.966453	1.035145	1.240134	1.578597	2.047064	2.642573	3.363406	–
20	1.702537	1.769919	1.971326	2.304863	2.768250	3.359667	–	–
25	2.636320	2.702655	2.901247	3.231062	3.690984	–	–	–
30	3.767271	3.833042	4.030230	4.358616	–	–	–	–
35	5.101354	–	–	–	–	–	–	–

When the sag $z(h, \theta)$ is expressed as a function of the angle θ while fixing the distance h, the sags at the points between the local maximum and the local minimum are interpolated by the

sine curve. That is a difference between the second embodiment and the second comparative example.

Accordingly, the second comparative example does not satisfy the condition (1) because the value of z(h,45)-{f(h)+g(h)}/2 equals 0, and the condition (2) is not satisfied because the value of the intermediate term of the condition (2) equals 0.

Figs. 17 and 18 are three-dimensional graphs showing transmitting optical performances of the second comparative example; Fig. 17 shows an average refractive power error and Fig. 18 shows astigmatism of the spectacle lens. Fig. 19 is a two-dimensional distribution map showing the astigmatism shown in Fig. 18.

Compared with Figs. 14 to 16, in the second comparative example, the contour lines of the astigmatism form rhombuses, which results in unnatural defocusing on the periphery of the view field. In the second embodiment, the contour lines of the astigmatism are almost oval, which results in a natural defocusing.

As described above, according to the present invention, since the gradients of the curve, which expresses the sag as a function of an angle, are different between the local maximum side and the local minimum side, the astigmatism in the directions between the first and second principal meridians are well balanced, which results natural view field.

The present disclosure relates to the subject matter contained in Japanese Patent Application No. 2000-317242, filed on October 17, 2000, which is expressly incorporated herein by reference in its entirety.